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Citation for published version:
Kosmadoudi, Z, Lim, T, Ritchie, JM, Louchart, S, Liu, Y & Sung, R 2012, 'Engineering design using game-enhanced CAD: The potential to augment the user experience with game elements', *Computer-Aided Design*, vol. 45, no. 3, pp. 777-795. https://doi.org/10.1016/j.cad.2012.08.001

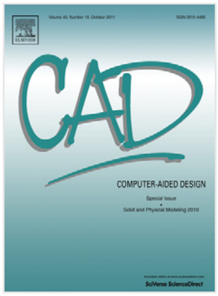
Digital Object Identifier (DOI):
10.1016/j.cad.2012.08.001

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Early version, also known as pre-print

Published In:
Computer-Aided Design

Accepted Manuscript



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PII: S0010-4485(12)00169-8
DOI: 10.1016/j.cad.2012.08.001
Reference: JCAD 1963

To appear in: *Computer-Aided Design*

Received date: 10 October 2011
Accepted date: 4 August 2012

Please cite this article as: Kosmadoudi Z, Lim T, Ritchie J, Louchart S, Liu Y, Sung R. Engineering design using game-enhanced CAD: The potential to augment the user experience with game elements. *Computer-Aided Design* (2012), doi:10.1016/j.cad.2012.08.001

Highlights

- The progression of the CAD's tools from the past to present.
- Introduction to game elements and their application for CAD.
- User experience and motives in games and engineering.
- Future Trends in CAD interface development.

Engineering design using game-enhanced CAD: The potential to augment the user experience with game elements

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Abstract

Since the coining of the term 'serious games' by Clark Abt, practitioners in fields such as education, the military, medical science, as well as researchers from other disciplines, have investigated with interest game mechanics and the dynamics of games in non-gaming applications. Gaming has extended beyond what was initially its natural boundary of entertainment and is now associated with the process of problem solving while providing analytical questioning of scientific viewpoints through active game-play. The rules of game interaction or game mechanics include the concepts of usability and playability which are focused in a less complex environment which provides a more intuitive user experience (UX). In the process of CAD development and applications the effective use and support of the user's perception and their UX have been compromised by the engineering design system's functionality and step-by-step evolution. This article reviews gaming techniques and mechanisms that may potentially be beneficial to the future development of CAD systems in engineering, in particular to maintain cognitive engagement. In light of this, the article focuses on the fundamental activity of engineering using CAD systems with particular attention on CAD graphical user interfaces (GUIs) and how they can be potentially enhanced using game mechanics to provide more engaging and intuitive environments.

Keywords: CAD; Engineering design; Games; User experience; Engagement

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1. Introduction

Gameware and game methods have seen increased implementation to address some limitations of conventional engineering systems. Games along with game hardware, such as Nintendo's Wii [1] or 'Wiimote' and Eye Toy [2], Xbox 360 Kinect [3] and PS3 Move [4], exemplify the move away from traditional computer-human interaction to that of invoking intuitive interaction which supports the natural human way of working.

Games have always been perceived as "fun" and engaging [5]. Coupled with technological breakthroughs in computer-human interaction, educators [6-9], medical scientists [10-13], and many others [14-23] are investigating the potential of gaming methods and technologies within their disciplines for a more effective, immersive and engaging learning/training.

As with digital gaming, advances in computer aided design (CAD) systems have seen the introduction of hardware devices, simulation and visualisation tools to improve interactivity and the understanding of the elements of the design [24-26]. Nowadays CAD is no longer about providing an environment for the designer to accurately construct geometry but one that has many added functionalities so that it can assume a multi-functional engineering environment incorporating analytical and computer aided manufacturing capabilities, allowing engineers to carry out multiple tasks. To further enhance CAD interaction, haptic [27-28] and vibrotactile [29] devices have been used in conjunction with virtual reality (VR). Unfortunately the interaction between the engineer and current CAD systems is not without problems. The functionality offered by CAD systems has come at a cost; the tools have become highly complex, requiring cyclical operations even for simple actions, making them cumbersome and difficult to work with [see section 2]. Complicated CAD interfaces tend to limit the satisfaction, efficiency and reliability of their use for its users [30]. Engineering design via CAD frequently involves delicate compromises between ideal designs, practicality, functionality and market forces, meaning poor user performance during can negatively affect the quality of the design as well as the productivity of the engineer. Games have been shown to generate cognitive engagement due to its inherent interactivity, and even inculcate confidence [31-32]. Then, perhaps enriching CAD environments by applying gaming methods may improve and enhance the effective use of the perceptual capabilities of their users as well as the quality of their output since gaming technology and the associated interfaces can potentially offer memorable and formative experiences to users. Indeed, in domains such as healthcare, studies have shown that in a more relaxed game-like environment the users experience a strong desire to accomplish tasks produce better results, for example, in rehabilitation [33] and surgical simulation training [34]. Therefore, from an engineering perspective gaming may present the opportunity for the development of next generation CAD environments to reduce design lead times, promote decision-making and sustain the engineer's interest and engagement.

A key phrase associated with games applied to real working environments, specifically educational games, is “Serious Games”. Serious Games have been explored for their positive effect on learning, their leisure and enjoyment factor [7] and it is likely that similar engaging features can be transferred to suit a CAD system user interface and experience.

This paper reviews the potential of gaming mechanisms useful to design engineers. The article focuses specifically on mechanical CAD in the geometric/modelling design stage of the engineering design process while considering game concepts for future CAD environments.. The paper is organized into four sections, namely: “The Limitations of CAD in Engineering Design”, “Digital Gaming”, “Discussion” and “Conclusion”. In section 2 (“Engineering Design using CAD”) a summary of studies investigating the usability of CAD graphical user interfaces (GUIs) is given and their affect on engineering design, mainly during the geometric modelling stage (geometry creation). Section 3 (Games”) outlines the key aspects of game elements and their application in non-game applications followed by a focus on the user experience concept with a short description of their potential application within CAD systems, summarising with a comparison of CAD and game systems. In section 4 there is a discussion of the key results of this review along with the possible future trends in CAD interface development followed by some conclusions.

2. The Limitations of CAD in Engineering Design

Commercial CAD systems’ developers have focused mostly on adding functionality in their tools sets, rather than upon making those tools fundamentally more usable [35]. CAD tools influence the ability of engineers to solve engineering problems both positively and negatively. CAD has come a very long way in assisting and supporting the product development process for products, particularly for those which would take considerable time to produce using manual processes. In a CAD environment the engineer can edit lines and model shapes quickly and accurately with accurate dimensions and scale. Today there are a variety of CAD environments ranging from knowledge-based [36-38] to parametric [39-40], from surface modelling [41-42] to physics based CAD [43-44], from mechanical (M-CAD) [45-47] to medical CAD [48-50] and from the common desktop-platform to virtual reality VR [51-53] and/or haptics [54-55] (Table 1).

Table 1 CAD Categories

Advanced CAD systems today include modules for 3-dimensional heat, stress and conditional analysis to test the viability of a digitally created object or product [63]. Engineers can visualise and evaluate new ideas [64-65] and promote communication between colleagues [66-67]. There are many features offered by CAD tools which facilitate the design, the authors have explored a variety of CAD packages and summarised some of these and their functionality in the Table 2:

Table 2 Current CAD functionality

While these features and their positive effects are recognised, there is a negative impact of CAD tools in engineering design which is still very much under research since they impact substantially on the design experience of the design engineer and on usability issues associated with CAD GUIs (Table 3).

For example, Waern's [68] empirical study reported that CAD users cannot remember all possible alternative methods for a design task. Instead the tendency was to learn a limited set of methods that worked well and then use similar strategies on new tasks. He concluded that users had difficulty in remembering menu items and other necessary design conditions to be applied. He suggested users would benefit from the system's feedback regarding the meaning and the conditions of the commands in use [69]. Waern also questioned the cognitive properties of the designers dealing with CAD. Since the designers have a limited knowledge of the CAD system, they adapt their design strategies to focus on known routines which may constrain their creativity because they are spending too much of their cognitive resources dealing with operating the CAD package instead of dealing with the task in hand. Likewise Cooley (cited by Parletun *et al* [70]) suggested that the temptation to use sub-assemblies from stored drawings may inhibit the creative phase in particular. Black [71] showed that students working in CAD felt that they were compromising their initial ideas more when compared with students working on paper.

Luczak *et al* [72] and Muller [73] looked at the efficiency limits of CAD systems due to system complexity. Muller [73] in his preliminary study involving 20 students with 40 hours of CAD training concluded that most operations in CAD do not produce drawing elements and that it takes a longer time to complete the same task in comparison with a drawing board. Luczak *et al* [72] studied 43 designers in 11 different manufacturing firms oriented in engineering tasks. Their hypothesis was that "*…with increase in mental capacity used for the manipulation of the CAD system, the task-related output decreases and the stress-strain level increases.*" From the results they concluded that, even when the subjects were highly trained, the high complexity of the commands, due to the many input parameters, restrictions, and requirements, led to low performance, reduced creativity, friction and frustration.

Bhavnani *et al* [74] explored the productivity in CAD using ethnographic techniques. His study involved 11 architects and 3 draftsmen from the same design branch using a sophisticated CAD system. Based on observational data, open-ended discussion with the subjects and video and keystroke recordings, he revealed that there is a suboptimal use of CAD systems whilst there is a lack of user's motivation to explore and find more efficient methods or commands for designing. They recommended active assistance while the user interacts with the CAD package. In a similar vein, Stacey *et al* [75] studied CAD system bias in engineering design, concluding that designers are pushed into creating designs in which the tools provided make it relatively easy to create. They also mentioned that the biasing effects of some CAD systems are due to inadequate human computer interface design.

Dickinson *et al* [76] reviewed the pen-template interface and other interaction technologies used during the design process and argued that the existing CAD systems - which are targeted at efficient, detailed drawing - cannot capture the designer's mental state during the creativity. They reported that the frequent use of mouse and menus seriously distracts the designer from creative thinking, concluding that mechanical engineering CAD users and developers should pay special attention to 3D mice, voice recognition and pen templates. These relatively new technologies provide more "natural" interaction mechanisms and have the potential to extend the CAD further into the conceptual and creative stages of design.

Petre [77] studied the early creative state of professional software and hardware designers in the design process. Her work extended over a six year period and focused on 3 successful companies from which 3 to 12 designers participated in the study. Her paper, based on observation data and design documents - e.g. informal notes and sketches for personal and discussion purposes made at meetings, on whiteboards, etc, - reported in detail the various informal and formal representations of early designs and how these were not well supported by existing CAD systems. Overall it was suggested that a designer's "ephemeral" and informal representations hold a great deal of information about the focus and the reasoning of the design and that an idea-capture tool that supports collaborative design should be implemented in CAD systems; this is similar to that demonstrated by Sung *et al* [78].

Lee *et al* [79] explored the usability principles in designing UIs for 3D parametric architectural design and engineering tools. The authors studied 10 state-of-the-art CAD systems, captured best practice and compared these to common UI principles creating a new refined set of UI principles for 3D parametric design tools. They concluded that 3D design systems have become overly complex since they are composed of several hundred menu items which cause cognitive load on the users which they cannot handle. They summarized 179 issues and categorized them into seven problem areas including dialog box design, drawing generation, the "Help" structure, a command menu structure, 3D modelling, toolbar layout and viewing and navigation. They also proposed a set of UI principles, namely: consistency, visibility, feedback, recoverability, maximization of workspace, graphical richness, direct manipulation, familiarity, customizability, assistance, minimalist design, and context recognition. The authors proposed these principles as a guideline framework for design or evaluation of UIs for 3D parametric modelling applications. They also suggested that those principles should be balanced, adapted and integrated with more general ones dealing with issues supporting innovative thinking and creativity.

Charlesworth's [80] recent study explored the way in which design students used virtual and physical modelling during design development. The study was based on 39 second-year product design undergraduate students who spent a day developing ideas on paper and the afternoon either modelling these physically or virtually. The study concluded that CAD has little or no value as a stimulus for ideas. Robertson *et al,* [81-82] also supports Charlesworth's proposition. They carried out an industrial case study using an online survey of 200 CAD practitioners from 32 different countries and found both positive and negative influences in the use of CAD in creativity. The positive influences were visualization and communication, whereas the negatives were described as premature fixation, circumscribed thinking and bounded ideation.

Table 3 Summary of studies in CAD usage

Continued improvements and technological breakthroughs, to support 3D printing, knowledge capture, design communication, collaboration capabilities, physical simulation, etc, have propelled CAD into the central role it enjoys in today's engineering design industry. Advances in hardware combined with state-of-the-art tractable algorithms have enabled CAD systems to become an essential integrated product design tool. However, these improvements have come at a cost through producing CAD systems which have become too complex to use. Usability studies in engineering design within CAD have revealed a plethora of issues regarding efficiency, usability, motive and the interaction of the users within these systems.

A summary of the current deficiencies and limitations of current CAD tools from the literature are:

- Complicated menu items or commands.
- Limited active and interactive assistance while deigning in CAD.
- Integration of informal conceptual design tools in CAD.
- Inadequate human computer interface design; focused on functionality but not in usability.
- Fixation on design routines.

3. Digital Gaming

Digital gaming is a complex but intuitive system comprising interactive technologies, media, and simulation technology [83], often with a story/plot. However, their interactivity is designed to be intuitive as well as stimulating the natural creativity and capabilities of the user. Games host a variety of challenges ranging from decision-making and problem solving strategies through to action reflexes [84].

The underlying goal of a game is to generate positive experiences for the players engaged in a gaming activity [5, 85-86] where *interactive play* is also referred to as “gameplay” [87], which focuses in the process of *use*, rather on the results of the process which tends to define the general use of CAD systems.

Understanding the complexity of gameplay experiences is difficult but it can be approached using the tetrad of Schell [88]: aesthetics, mechanics, technology and story (Fig. 1).

Fig.**1** Game elements and the user experience (UX)

Beside these four elements there are other supporting essentials important to the development of the game experience. These are: (i) the psychological aspects of gaming, i.e. the user experience (UX); (ii) game mechanics which are the tools for structuring and providing the game play [89]; and comprise rules, defined behaviours and user actions which offer rewards, challenges, specific goals and the motivation to reach these [90].

3.1 The Operational Elements of Gaming

3.1.1 Game Mechanics

Game mechanics connect player actions with the game content and challenges (e.g. variable difficulty level) and is part of the design and usability of a game [91]. There are a number of game mechanic definitions useful for the formal analysis of game structures that open up the possibility of connecting game mechanics to engineering design (Table 4). Also there are many defined game mechanic elements that are currently being used in game design industry; a selection of these is presented in Table 5.

Table 4 Game Mechanics definitions based on the paper of Sicart [92]

Table 5 Game mechanics elements [93]

As can be seen from these tables, there is no obvious definition of game mechanics. Some of the definitions relate the game mechanics as a summarised set of rules of the game system itself, whereas others define these as a design document for everything that the user can and cannot do in a game. However, most of these aspects listed relate to user interaction with the game system and the possible actions a user can take during this experience; however, there are specific goals in the game world and game mechanics define all the possible actions as means of the user’s guidance to reach these particular goals or to have a particular behaviour. In contrast with CAD where the goals are defined externally of the actual design system and there is no user constrains or defined possible actions in a form of guidance.

In summary the key aspects of game mechanics are:

- A player’s possible actions in the game system.
- A player’s actions design document.
- A game system’s set of rules.

3.1.2 Aesthetics and the Graphical User Interface (GUI)

Gameplay interactivity is closely coupled to the visual aspects of the experience or, more specifically, the “feel” part of what the user sees, i.e. visual perception. “Game” aesthetics can be defined as sensory phenomena that the player encounters in and during the game: the visual, aural and haptic experience of gameplay. Game aesthetics can also be defined as an expression of the game focused on the “aesthetic experience” [94] which is being applied through the graphical user interface (GUI) of the game. The GUI can be described as any highly-customised on-screen information that provides information, with successive layers of complexity or levels of play, concerning, for example, player status with action menus, maps or additional scene graphics giving the player more control when manipulating objects during game-play [95].

A game GUI differs from other GUI designs due to the nature of this highly interactive and intuitive environment. There are diegetic GUI elements which exist in the game world and both the avatar and the player can choose to interact with them through visual, aural, speech and/or haptic technologies in multiple integrated representations [96-97]. Also there are non-diegetic GUI elements which can be described as completely customized to ensure a familiar experience for the players [96-97] (Fig. 2). There can be also random or humorous GUI elements to sustain player’s curiosity, thus interest [98]. Moreover there are game GUI communications strategies to minimise user disruptions, e.g. users are not required to dismiss, acknowledge or address GUI elements [99]. Finally it is worth mentioning that the GUI is also connected to the game engine and handles the input and output of the users through mouse, keyboard, or force feedback devices like joystick or more intelligent game controllers such as Nintendo Wii [1], Sony Playstation Move [4], and Microsoft Kinect [3].

Fig. 2 Game UI elements [96]

Game aesthetics represents the front end of the game play experience and are directly associated with the user experience. A game GUI is designed to support the context of the game: the information and feedback resources. Moreover provide a high degree of customisation of interface layout and mapping of input controls and functions. In contract with CAD systems where there is not any communication strategy between the system and the engineer and customisability can be an issue [97].

In summary, from the literature, the key aspects of aesthetics and graphical user interface (GUI) characteristics are:

- A combination of representation tools (visual, aural, haptic) for the user's experience of the gameplay.
- Multiple integrated representations.
- An interactive and Intuitive GUI and metaphors.
- Customisable GUIs.
- Random or humorous GUI elements.
- GUI with communications strategies.
- Interactive devices variety.

3.1.3 Games Technology

Games technology is essentially the medium through which the game aesthetics take place, in which the mechanics will occur and through which the story will be told [88]. Early computer games consisted of little more than event loops and simple graphics routines to support 2D games such as Space Invaders [100]. The release of the game Doom [101] in early 90s ushered a new area in the game design and play. Doom achieved a high level of realism, animation and introduced the multiplayer play over the network. After Doom and its variations appeared, the game industry boomed and the inception of network play and its client/server architecture became commonplace, e.g. in large scale military simulations like SimNet [102] and VR development environments like World Toolkit [103] or languages such as the VRML [104]. As games' technology advanced, games become more demanding and more sophisticated game engines were developed in games such as Quake III Arena [105] and Unreal [106]. Nowadays game engines are geared towards believability, with their enhanced graphics, physical modelling techniques, animations with set of constraints, advanced geometrical models and real-time rendering.

3.1.3.1 Game Engines

Modern computer game engines such as Doom [101], Quake III Arena [105], Unreal [106], FrostBite (battlefield 3) [107] contain well-tested implementations of visualisation and interaction. Unity [108] and CryEngine [109] are well known for their simulation of Newtonian physics. The power and the maturity of these game engines have enabled them to be applied in areas for which they were not originally designed, such as architectural design [110-113], construction [114], military simulations [115-118] or other applications for scientific visualisation purposes [119].

A game engine is at the heart of any game and consists of five major components: the game logic, the physics engine, the rendering engine, the graphical user interface (GUI) and the audio engine [120]. The research presented in this paper concentrates on the game logic, physics engine and graphical user interface (GUI) aspects since CAD systems have their own rendering system and there has not been any development for the integration of any sort of audio engines.

Game logic relates to game theory and is an extension of game algebra [121]. It is a set of procedures or processes that are directly associated to reasoning that define how the game flows either autonomously or when the user interacts with it.

Physics engines are responsible for calculating the details of physics simulation [122]. Coumans [123] described the physics engines as responsible for the task of "breaking" 3D geometrical objects, i.e. where 3D geometry is prepared, for example, with Voronoi diagrams (Unreal Engine), Boolean operations, convex decomposition or tetrahedralization. In many games destruction and fracture effects (creating of 3D geometry and then the breaking of the object with the use of physics engine when playing a game) are part of an animation triggered to play at runtime, as long as there is no two-way interaction required on the fractured object, using a method called canned animation [123]. Other methods regarding how destruction occurs include real-time Boolean operations, particle based methods, finite element method based method and rigid body and hybrid based methods (Table 6).

Table 6 Physics engines' destruction methods based on [123]

Since "Doom" [101] in 1999, game engines have evolved into real-time 3D engines capable of representing complex 3D dynamic environments with continuous innovation in content and control - in contrast with the CAD which has been focusing more in its multi-functional engineering environment and recently in visualisation and the use of virtual reality (VR) [128] - Game engines comprise of the game logic, physics engine, rendering engine, graphical user interface (GUI) and the audio engine.

In summary, the literature shows that game engines define the following key aspects of game play:

- Game flow though the game logic.
- Dynamic content and control of the game through the physics engine.

3.2 Applications of Game Elements in non-game applications.

3.2.1 Game Mechanics for Serious Games and non-game applications

Recent research on game mechanics and game theory has increasingly transcended traditional game boundaries by embedding aspects of the game experience to enhance non-game systems' functionality, e.g. for interactive design, planning or digital marketing. The idea of taking entertaining and engaging elements from games and using them to incentivise participation in other contexts is being increasingly studied in a variety of fields (Table 7). One field which have been strongly influenced by the game context is education. In this, the approach taken is known as Serious Games [129] with the aim being to provide an engaging, self-reinforcing context in which to motivate and educate students [130].

Serious games encourage active and critical learning through game environments where, users enjoy the process of pursuing challenging tasks, achieving goals by making decisions, formulating strategies, construct knowledge, try different alternatives and succeed or fail without worrying about the consequences in real life [131]. Moreover these environments involves some aspect of competition [132] where the user try to influence the final outcome of the game process and at the same time feels attracted to the outcome [133-134]. Such behaviour can be described as intrinsic motivation, which has been recognized to be the one of the mechanisms of exploration and curiosity [135]. Examples of such serious games can be found in the following paragraphs:

To aid the understanding of physics, games such as the Bridge Builder [136] and Fluidity [137] are popular where they convert physics into constructive puzzles and users need to construct a series of puzzle mazes to build up a system's water power (fluidity) so they can proceed to the next level. For Bridge Builder the user must build a bridge to withstand the weight of a passing train bearing in mind the material costs and tension and pressure of the bridge under the train's weight. There are many similar games to be found online [138].

In engineering, the Concurrent Engineering Simulation Game or COSIGA [139] is a simulation game for product development within a CE (Concurrent Engineering) domain introducing the concepts of parallel and co-operative working in a distributed environment. In this game the users begin with a product scenario (e.g. truck) and go through the simulated product design process - from market specification to production (Fig.3). Through the game there are constraints that the user needs to be aware of, such as purchased components (specification, quantity, quality, supplier), stock levels [140].

Fig. **3** COSIGA: Product design and project management for scenario truck [140]

In business management courses there are a few examples of using games to enhance the user experience to assist the learning of planning skills and the development of business strategies; indeed, the popular strategic-simulation game The Sims [141] has been converted into a game for managing airlines, called the AirwaySim game [142]. The game itself has different scenarios and involves realistic aircraft data with economy models (airline passenger demand, fuel price, inflation rate etc.) finance management, staffing, marketing and generally everything that has to do with managing an airline company. Using the same concept the game called Business Tycoon [143] is also an online strategic game with construction and management simulation. The aim of this game is to attract customers, make profits and expand the business into an international co-operation. Also games such as Capitalism [144], Hollywood Mogul [145], Virtonomics [146] and Industry Player [147] are all strategic business simulation games based on real economic models.

There are also serious games with a social impact, such as Food Force [148] which aims to educate users with regard to the causes, effects and solutions of famine in third world nations. The game called Re-Mission [149] is designed to educate cancer patients about effect of cancer in their body. Darfur is Dying [150] is a game that seeks to inform the users about the conditions in which people live in the warring region of Darfur in Western Sudan. The Reach out Central [151] is an interactive soap opera style game for young people to work out their problems.

Other domains which use game mechanics as a different approach for interaction are: medicine, military, marketing, software engineering and engineering optimisation methods [152-157].

In medicine games are used to train young doctors; the Triage Trainer [152] is a game about the process of prioritising the treatment, Pulse [153] is another game for practicing doctors' clinical skills and Dental Implant Training Simulation [154] is a simulation environment for dental school students to diagnose and practise dental implant procedures.

In the military using game mechanics for training purposes has been applied extensively from assembling armour in a Lego-like system called McCurdy's Armor [155] through to tactical and combat training with games such as the Virtual Battlespace 1 & 2 [118], and the Virtual Combat Convoy Trainer (VCCT) [156], American Army [117] and Secure the Deck [157]

In online marketing, game design has been adopted to incentivize desirable user behaviour; collecting badges, in Foursquare [158], levelling up in My Starbucks Rewards [159], and travel leader-boards in Tripit [160] (Fig. 4). Also the ability to increase sales and improve the customer experience with virtual “configurators” can be found in Dell, Suzuki, and Samsung products with the EON Reality [26].

Fig. **4** Game mechanics applications in marketing brands [161]

In software engineering, the Visual Studio (Microsoft) platform has been developed to include a gaming add-on track for coding activity; for each successful compilation, achievements awards are obtained based on certain programming tasks completed. A leaderboard is also hosted by Microsoft for competing with other programmers who have installed the add-on [162].

Table 7 Game Mechanics and their effects in the specified domains

Strategic interaction based on the game theory, the rule based system of a game and an alternative definition of game mechanics (see table 4, Cook (2005)) has been exploited not only by economic theorists but also in engineering design. Vincet [163] suggested the game theory in engineering design; *"...encompasses not only the familiar concept of scalar optimisation, but the lesser known concepts of multi-criteria optimisation and multiple optimisers as well."* Since that study there has been an increased focus in the decision making in engineering design in combination with game theory.

Rao *et al* [164] illustrated a game theoretic framework for design modelling in a strategic multi-player game concept. They stated that design is often a collaborative activity with different decision makers (designers) responsible for different stages of the design. One decision maker chooses one dimensional variable vector *x*, and *p* is a variable that has no control over it, and *X* is the state of the design with $0 \in x - X(p)$. The decision maker simply tries to find the *x* to obtain a satisfying or feasible design. However the *p* is controlled by another foreign decision maker (leader). Will the foreign designer always select *p*? The conflict between the hypothetical designers (follower/leader) for obtaining a satisfying or feasible design, resembles the strategic game of "Prisoners' Dilemma" [165] where one player controls x and the other player controls *p*. The authors have described the system design as *"...a game which consists of multiple decision-makers or players (or designers, in this case) who each control a specified subset of system variables and who each seek to minimize their own scalar cost function subject to their individual constrains."* To illustrate their concept, they present two case studies (a pressure vessel and an axially symmetric rotating disk) each with different objectives. They concluded that game-theoretic concepts play an important role in design modelling and that the future challenge will be the realization of the importance of strategic game models in design studies and the development of robust numerical methods to solve the resulting multilevel nonlinear programs.

Lewis and Mistree [166] studied the same concept in the context of product realization with three different types of interactions: cooperative, non-cooperative and leader/follower, leading to a game of decision making processes between multiple teams each of which controls a subset of design variables and seeks to minimize its cost function subject to individual constraints. They applied game theoretical implementations on an aircraft study and concluded that game theory can be used to model decision-making processes by abstracting these processes as a series of games and analysing their results into structured design problems.

Chen and Li [167] studied the role concurrent product and process design (CPPD) via a design team and a manufacture team and their interactions towards achieving an ultimate, unified design. The design team's aim was to optimise the overall product functionality whereas the manufacture team's aim was to minimise manufacturing cost. The developers envisioned the teams' design activities as a multiplayer game, the members of the teams as game players and their interactions (cooperative, non-cooperative, and leader/follower) as strategies derived from game theory. The authors used satisfaction metrics as a basis to frame both teams' design preferences.

Finally Xiao *et al* [168] studied game theoretical principles in the relationships between engineering teams and their collaborative decision making based on the three types of game interaction: cooperative, non-cooperative and leader/follower.

3.2.2 Game Aesthetics & GUI in non-game applications

Game aesthetics have advanced significantly over the last few years and there are some aspects of these which have been implemented in non-game systems. Nowadays 3D GUIs extensively use motion sensing, physical input and spatial interaction techniques to effectively control highly dynamic virtual content [169]. Game's GUI and other game industry applications parallel ongoing work in the virtual environment community [129]. Gershon *et al* [170] suggested that digital games fuse software engineering, architecture, artificial intelligence and 3D graphics with dramatic performances, music and storytelling. With game devices such as Nintendo Wii [1], Sony Move [4], and Microsoft Kinect [3], game developers and researchers now have the opportunity to create low cost, compelling interfaces and game-play mechanics that can make use of these technologies and learn from successful past (high cost) system research [171].

Unlike most computer applications, where the interface serves as means of interacting with some underlying functionality, the sole purpose of a game's interface is for the user to be entertained whilst engaged in game-play; therefore, games with cumbersome interfaces seldom succeed in the market place [172].

Game GUIs and game devices have been used by researchers for several purposes. Chao [173] used the computer game Doom to develop a process management system (task manager). The main function was to run the computer system's processes which were instantiated as "process monsters" in a "dungeon". The program periodically polled the operating system to add newly-created processes (and so monsters) to the game. When the "monster" accumulated enough damage and is killed then the associated process is also killed. The system provides a natural control mechanism for processes in a heavily loaded system. Maxwell *et al* [174] designed their robot's interface based on the "First-Person Shooter" (FPS) genre game. The integration of FPS with the Urban Search and Rescue (USR) robot interface included status area, radar and maps so can provide the remote operator a feeling of awareness. The system worked well especially for the users with gaming experience. Stubbs [175] designed a game-style interface for basic Japanese character recognition. The author, inspired by the game “The Typing of the Dead” (a first-person shooting game), developed a computer interface to help Japanese students to learn to read more effectively the phonetic alphabets of kana. The users need to kill zombies by typing the correct Romanization. When a user kills a zombie circle symbols appear to indicate the score. The author’s pilot study concluded that the students increased performance after they used the interface and that this may be a good indication that game interfaces prove to be beneficial to users outside of the context of pure entertainment.

Drury *et al* [176] used video games as an inspiration to improve user’s interaction with airborne robots known as Unmanned Aerial Vehicles (UAVs). He reports that UAV operations are similar to many video games as they require the players to understand the location of important objects in the 3D environment and undertake fast-paced activities. He developed a video game-based framework (VGBF) and proved its applicability by comparing the user interface characteristics of two UAV ground station implementations.

There is much reported work on using gameware (e.g. Wii Remote) for a variety of purposes, such as for gesture recognition based applications [178-180], robot control [181], medical data interaction [182] and others [183-184], Izadi *et al* [185] developed an interactive reconstruction system called KinectFusion and their system collected live depth data from a moving Kinect camera to create accurate geometric models in real time. Kang *et al* [186] suggested that the size of displays have increased (for example the VR screens) to the point where it difficult to control an application using a keyboard and a mouse. He proposed a gesture recognition method based on Kinect system for controlling the mouse pointer in 3D applications. Norrie *et al* [187] described a mobile application that supported special interaction by using the 3D position data from the Kinect to simulate a proximity sensor. She concluded that the system was reliable enough to create compelling augmented reality systems to emulate a range of virtual sensors.

3.2.3 Game engines in non-game applications

Game engines have been used extensively in the entertainment sector but a huge industry exists around not just the content of the game (i.e. entertainment) but also the technology (the engines) behind them. Such industries include the construction, military, medicine and education.

For medical training game engines allow for a relatively quick creation of visualization and interactive scenarios. The game engine Blender [188] and its physics engine, Bullet, have been used for the visualization of blood flow [189] and also using its built-in volumetric material for the visualisation of microCT 3D dataset [190]. Marks *et al* [191] evaluated game engines for simulated clinical training. The authors chose the Unreal Engine [106], id Tech [192] and Source Engine [193] and tested them based on the criteria of stability, availability, the possibility of custom content creation and the interaction of multiple users via a network. They concluded that game engines are a good foundation for inexpensive clinical training applications. The game engines' features of graphics, audio and network capabilities are developed to a degree that allows the developer to focus on the content rather than on the details of implementation. Moreover the physics models for the simulation of basic soft tissue are possible with game engines. They concluded that the continuous development of game engines brings new features (geometric models that can deform arbitrarily by displacement textures, physically correct simulation of smoke and liquids) that can be used in medical scenarios for a more realistic simulation.

In construction and civil engineering, Juang *et al* [114] developed a game-based construction simulation environment. With the use of the game engine called Blender [188] they implemented a forklift simulation to be used for the manipulation of an actual forklift. Their results showed a high degree of realistic simulation and a satisfactory interaction between user and compute.

In military training simulations are almost driving the development of game engines by creating game engines such as Delta3D [116] specifically for this purpose. As mentioned in section 3.2.1 there are many military training applications. The American Army [117] is based on the Unreal game engine [106] and Virtual Battlespace 2 [118] is based on the Real Virtuality 2 game engine [194]. Prasithsangaree *et al* [115] develop the Unreal Tournament Semi-Automated Force (UTSAF) software which integrates a commercial off-the-shelf (COTS) game engine for military simulation.

In education there is similar trend of developing specialised game engines for educational purposes. The STEAMiE Educational Engine (SEE) [195] is a high-fidelity physics engine for creating educational games with game topics of position, velocity, acceleration, kinetic and potential energy, projectile motion, transfer of energy, pendulum mechanics, friction and bilingual as well as entertaining video games. SAGE, Simple Academic Gaming Engine [196], and Alice [197] are another two educational game engines designed to teach computer science and game programming to undergraduate students. Second Life is a multiplayer online virtual world that can be used to develop educational games [198].

3.2.4 Summary

Examples of serious games in non-gaming applications are physics games, engineering games, business games and social impact games. In medicine and military game mechanics assisted in developing applications for training. In marketing, game mechanics were adopted to incentivize desirable user behaviour. Game theory has been applied extensively in optimising the decision making in the different stages of the engineering design stages. Game aesthetics, GUI, gameware and game engines have also been applied in non-game applications; from a computer task manger with system processes presented as monsters to Urban Search and Rescue robot interfaces designed to be similar to First-Person Shooter games, to gesture recognition applications to medical date interaction, to military and educational games. All of these demonstrate the potential for these types of applications being applied in another non-gaming environment, namely engineering CAD.

3.3 User Experience

User experience (UX) is a term adopted by the human–computer interaction (HCI) community, meaning ranges from usability and beauty through to the affective or experiential aspects of technology and people interaction [199]. There are a number of models and theoretical approaches that have been developed to understand the experience.

Hudspith [200] presented the UX as a theoretical model to help developers understand how people interact with their products. He provided three dimensions namely utility, ceremony and appeal. Cain [201], using a similar concept, defined the categories of "think, do, use". Hassenzahl [202] used a model of traditional-goal and task-based thinking with fun and action-oriented modes of behaviour to describe peoples interactions. Wright *et al* [203] explored the UX as an interaction model from a design perspective. He proposed that people's actions create meaning which can be described through four threads: compositional, sensory, emotional and spatio-temporal. Pine and Gilmore [204] differentiate between active and passive UX and immersive vs. absorbing UX. Overbeeke *et al* [205] focused on aesthetics and behaviour feedback. They suggested that information and action in interfaces can be categorised in six ways: time, location, direction, modality, dynamics and expression. Hassenzahl and Tranctinsky [199] have presented three prominent perspectives beyond instrumental (holistic, aesthetic, hedonic), emotion and affect (subjective, positive antecedents & consequences) and the experiential (dynamic, complex, unique, situated, temporally-bounded). Each one contributes equally in the understanding of user interaction with technology. However they concluded that UX is a consequence of user's internal state (e.g. motivation, expectations), the design system (e.g. functionality, complexity) and the content within the interaction occurs (e.g. organisational setting) that creates the innumerable experience opportunities. Thus none of the perspectives above fully captures the UX.

The current interest in UX focuses on aspects beyond the functional and usable characteristics of a HCI. Today's UX is driven by the *positive* experiential and emotional state of the user during the interaction with a product [199]. Flow theory in psychology [206] and video game design have become perspectives for exploring this positive experience [207].

3.3.1 User Experience in Games

The UX in games is founded on the components of game mechanics, user interface and narrative (storytelling) [194] but also evolves from the gameplay. Gameplay is defined by the *"...users' actions that need to be performed in the game to reach an explicit goal, where one failure can provide the basis for a new attempt, or succeed and give acknowledgments and metrics of how well the user has done"* [208]. The goals, feedback and the mixture of failure and achievement provide an engaging state with the events of the game accompanied by rich emotions, which are an essential part of playing games [209]. The motivational aspect of the gameplay can be presented as challenges, sensations, feelings and narrative [210-211]. Also, motivation can be explained by rewards and achievements [212].

There are many studies providing a useful list of game-relevant issues and cognitive models that aid the understanding of the outcome of the experience [213-218], as illustrated in figure 5. They are usually associated with the term immersion [219] which can describe some aspects of concentration [220]. Moreover the states of flow, describing an "optical experience" [221] and presence, in a sense of "being there" [222] are another two terms associated with this positive experience.

Fig. 5 Diagram summarizing the game-relevant issues and models

The UX is becoming central to the understanding of technology usability and HCI. There have been attempts to understand UX (see section 3.3) but none have fully captured its essence, since, during the gameplay, the player goes through a variety of use experiences which can be emotionally appealing and fun or negative. Games has given a new perceptive of how UX explore the emotional dimensions of interaction; from the aspects of immersion and motivation to the states of flow theory.

Therefore, the literature shows that with regard to UX, those aspects which are potentially relevant to future development and aid the usability issues in CAD (as presented in section 2) are:

- Variety of Experiences.
- Engagement and motivation.
- Emotional appeal.
- Immersiveness.
- Sense of presence.

- Cognitive models and metaphors.

3.2.2 Game-based Engineering, UX Components Enhancing the CAD User Experience

Game UX components cannot all be relevant to engineering design and CAD but some might. The careful crafting of user's experience through a system of interaction such as a game is critical to the design of meaningful, motivational and engaging "play". Experience has to incorporate not just explicit interactivity but meaningful choice ("micro" or moment to moment choice and "macro" choice which represent a chain of micro choices), meaning that when a player makes a choice in a game, the system responds in some way [223]. As highlighted previously, UX plays an important role in games; however, this does not seem to happen in engineering design using CAD. Indeed, within CAD, users have plenty of choices that they can make, from the object conceptualisation to geometric relations; however the interaction with the actual design system is limited.

There are no specific studies regarding games' UX components in engineering design; however there are a few studies in cooperative modelling between a human and computer systems which reflect what has been defined as UX in games.

In his study Kochhar [224] explored the benefits of cooperative CAD (CCAD) as a system that generates alternative partial developments of the initial design based on a "language" (a grammar-based description of the design process) of valid designs (Fig. 6).

Fig. 6 CCAD system architecture [224]

CCAD provide users with an automated assistant for exploring alternative ideas by providing just a "backbone" or initial design and some indication of the goals criteria. The users control the combination of manual and automated design by applying grammar rules (Fig. 7).

Fig. 7 Selecting specific rules for research alternative ideas [224]

Additionally, the designer can use the grammar to describe specific rules of a design (Fig.8). The CCAD system then produces alternative floor designs for the user to choose from and transfer to the modelling stage/system (Fig.9).

Fig. 8-9 Rules for subdividing the house into night and day areas and the interface of browsing through alternative designs [224]

Hu *et al* [225] proposed another interactive co-evolutionary CAD system namely ICE-GCAD. The CAD system is for garment pattern design and supports collaboration among inexperienced designers and experts. The system collects evaluation scores; these scores are given by the experts in the field based on a detailed factor list. Then the system's algorithm searches the optimal designs by immune evolutionary operator and generates alternative designs (Fig. 10).

Fig. 10 Data flow in the interactive co-evolutionary GCAD system [225]

Huang et al [226] also presented their views of the interactive design process to improve users' efficiency and quality in system performance. The authors presented an interactive design system that allows users to provide input parameters to the analysis models, observe the analysis result, and optimize the product design (Fig. 11). By illustrating a coal pipe design case, they were able to reduce the total computational time for the case by more than 40%.

Fig. 11 Diagram of the System Architecture [226]

Game UX approach differs greatly with CAD. Games actively encourage a variety of experiences, while design environments like CAD strive at consistency at all times. Game UX is focused on interactivity with the game system in a way to enable the player to visualise the impact of his/her actions and encourage him/her to learn through strong feedback mechanisms (in combination with the game elements). However, attempts have been made with varying degree of success in interactive content and control in CAD [224-226], to improve users' efficiency and quality experience.

3.4 Instances of Game Systems in CAD-type Environments

A recent example of using game mechanics in CAD is the adoption of a "human-centric" approach. Via the Manikin extension from Pro/ENGINEER [227] which provides avatars, 3D digital human models can be used inside a product model. The "manikin" is customizable and fully manipulated in real time helping the designer to better understand the relationship between the product under development and its users.

A clever use of game mechanics for CAD was in "The Monkey Wrench Conspiracy" (MWC) project by Thinkdesign Company. This project was a First-Person Shooter (FPS) style game like Doom and Quake, aimed to train design engineers to learn to use the Think3D CAD system (TD) [228]. The marketers of Think3D CAD observed young engineers (20-30 years old) working in CAD and they suggested a game approach to reduce the steep learning curve of their system [229]. In the MWC game, the players build tools (Fig. 12), fix broken parts, and defeat traps. The game's aim is to engage engineers to move from the 2D CAD systems into learning complex 3D CAD, but at the same time having fun, be motivated and be certain after the finish of the game that they can use CAD competently [229].

Fig.12 The Monkey Wrench Conspiracy CAD-game interface [230]

Another example of investigating game mechanics and game engines for engineering design in CAD was provided by the pilot study of Kosmadoudi *et al* [231]. The authors demonstrated how a game-like environment which incorporated racing simulation, based on a physics engine, after the design was completed compared with a commercial CAD package without the game elements and whether or not this would have any significant effects on user experience (UX). The experiment involved four engineering students creating a 3D model of a robot or a spider using the game-like 3D design environment called BAMZOOKi [232] and the 3D CAD parametric feature solid modelling software package Solid Edge V.20. To track the "experience" of the users while interacting with the applications, their psycho-physiological states, brain waves or electroencephalography (EEG) and stress levels (via galvanic skin response (GSR)) were measured using a biofeedback device. The results indicated a more positive response to the game-like environment (Fig. 13).

Fig. 13 Participant's GSRs while designed in both interfaces. The top line is the GSR in Solid Edge and the bottom in BAMZOOKi [231]

There are some studies which outline the application of gaming elements focused in game aesthetics and GUIs for engineering; one example is Koji [233] who built a 3D highway modeller using a driving game interface. The results showed that the driving game interface was useful and fun as a design tool compared to previous conventional design system. Fiorentino *et al* [234] investigated the feasibility of CAD modelling using videogame devices. Integrating Wi-mote and Nunchuck into a commercial mechanical CAD using simple scripts to map the Wii input into CAD commands, they compared the modelling task times of the user with that configuration to the standard 2D mouse-based interface. Based on the satisfactory results from the user's interaction using the Wii input the authors concluded that there is a possibility in use of gameware in next generation of CAD tools for direct modelling.

Gallo [210] explored the representation of medical data and presented a glove-based interface for 3D medical image visualization. He described a 3D user interface integrated with a Wii-mote enhanced wireless data glove as the input device for exploring medical data in semi-immersive virtual environments. According to Gallo, radiologists are not inclined to use tools with time-consuming training and system configuration; there is a need for user interfaces with minimum cognitive load together with intuitive and effective interaction techniques, since the *"...activity of medical image analysis is executed many times a day by different clinical practitioners."* Future work is focused on the evaluation of the hybrid data glove together with the interaction techniques as we have seen in the cable harness design application of Ritchie *et al* [235].

Tsang *et al* [236], incorporated real-time navigation with real-time responsiveness for the inspection of virtual 3D objects [Fig. 6]. The authors in their project called "Boom Chameleon" developed a device consisting of a flat-panel touch screen display mounted on a mechanical arm tracked in 3D space which displayed functions as a physical window into 3D virtual environments; by moving the device, its display in physical space changes into the corresponding viewpoint in the virtual space. The device is also configured to record the 3D viewpoint by touching the screen, providing verbal feedback through a microphone, and pointing/drawing through the integrated flash tools for highlighting or drawing. A Snapshot tool is also included. The devices' rich interaction is similar to video and computer games' real-time responses to user input where players move through the game world while triggering actions. From the users' interactions with the device the authors found that the users have immediately understood the navigation mechanism and quickly learned to control the viewpoint and the patterns of *"...navigation, pointing and voice are all interspersed within the same short periods of time."* They concluded that the use of game concepts in virtual design create a compelling user experience and aid in the construction of a high quality interaction.

Fig. 14 Experimental components of games [236]

In engineering a virtual environment called Virtual Training Studio (VTS) has been developed where users are trained to perform predefined assembly tasks [237]. The user is being assisted, if necessary, in the form of video clips, 3D animations and also with a 'virtual mentor' component that monitors the user and offers help if repeated errors are being performed. Sung *et al* [78], reported an industrial case study on knowledge capture methods in the design and manufacture. The authors demonstrated benefits of virtual reality as a computer-based design tool over CAD methods. The experiment, using the Cable Organisation System Through Alternate Reality (COSTAR) system, involved designing a cable harness design with industrial engineers wearing a head-mounted display (HMD) and using a magnetic tracking system with pinch gloves. Part of the results was focused on the usability of the system, where the participants provided positive feedback about the COSTAR system: *''Comfort in design of environment/accurate representation of depth''*, *''Prompting for design change reasons in the interactive help is useful and quick''*, *''Standardising and asking for design change descriptions in this way would be great in a CAD system...'', ''Having a feel of manually routing cables in a system''*. Although not game applications per se, these do demonstrate how novel ways of enhancing the user experience through game-relevant aspect can provide benefits to the engineering experience through more enjoyment and engagement; similar to some of the factors associated with games interfaces and UX.

4. Discussion, Potential Future Trends & Research Issues

The tools that engineering designers use exerts a powerful influence over the products they develop. CAD systems have become central to processes from the earliest design phase to final production; they influence the entire life cycle of manufactured products. CAD systems have integrated tasks ranging from design specifications and product analyses through to CAM and production tooling design by using links to appropriate geometric data, visualizations and interfaces with a variety of software packages. CAD systems have enabled the communication of the design, development, analysis and manufacturing. On the other hand the current sophisticated and advanced development of CAD systems have an impact on engineers' design performance and interaction experience. When dealing with the current design-in-CAD what are the key issues that arise when addressing the question: *"What does it take to make an efficient engineering design environment for promoting decision-making and sustain the user interest and engagement?"* Is the answer rooted more in a usable design system (e.g. an effective GUI), in training, in positive attitude towards CAD learning, in CAD design experience or in suitable behaviour traits? The authors believe that the likely answer is a combination of all of the above. While factors such as technical background (CAD design experience, engineering know-how), learning preferences and engineering design tutoring have been researched extensively, other important factors go unexamined. These other factors, such as user experience and usability theories, may prove to be as critical as their technical and personality traits

There are studies which present usability problems in CAD (section 2); however there are very few suggestions with regard to how to solve them and the authors contend that game elements have the potential to enhance this aspect. Regarding the engineer's user experience and interaction in a CAD environment, there is also a lack of research in this area. Although usability and user experience research in CAD is extremely limited, in game systems it has been the main focus since the 1990s when the first game engines were developed. As has been shown, games are an extremely influential form of computer software and have been the most engaging interactive system. The level of popularity is reflected not only in the economic success of games but also in them becoming more and more a part of society's general cultural awareness since they impact on nearly every aspect of people's social lives and interactions. With the move towards serious games, games have become a new way to educate, train (military, medicine etc), socialise (e.g. Facebook) and work (Visual Studio, development platform, gaming add-on, VR assemblies and design). Do games provide a promising approach to understand the human computer interaction (HCI) (usability and UX aspects) in digital engineering systems such as CAD and can they potentially affect – in a positive way - the engineer's user experience?

Of course, the practices are defined somewhat differently for games systems than for CAD. The core definition of success for a game is that a person enjoys the game enough to keep playing, rather than it helps a person achieve a task. The game has a crafting and compelling "feel" to it, a moment-by-moment interaction as the system responds to the player; not an end-use experience such as within CAD.

With this in mind, in Table 8, a summary is given of the general game characteristics based on the main game elements obtained from the literature review. These are compared with the key characteristics found in current CAD systems and highlight the potential for possible "gaming" effects which could potentially be embedded in the latter and are worth researching.

Table 8 Game elements and characteristics compared to the relevant limited CAD aspects

The potential CAD-relevant game effects which require further investigation are:

- Challenges & rewards.
- System specific goals.
- GUI Immersion.
- Curiosity.
- Information complexity and knowledge structures with communication strategies.
- Fantasy (or "...*the integral and continuing relationship with the instructional content being presented*." [238].

Based on the substantial use of game technologies and game elements in a variety of disciplines and highlighted in the literature, the authors believe that the future trends in games and engineering design will focus on developing existing CAD systems to enhance training applications, interactive product visualization and interaction, provide enjoyable and naturally intuitive interfaces and real-time simulations, providing new types of positive experiences for engineers. Configurators (see section 3.2.1) have already been developed for easy and interactive customer product customisation and there have been demonstrations of converted large CAD files being used in real-time engines [239]. Also another focus could be the use of novel combinations of sensors since CAD systems are still far from providing sufficiently versatile user interfaces; these will allow the embedding of these in mobile tablets and other display platforms to load objects, and recreate those visually using real-time 3D visualisation tools. Moreover CAD will integrate automated knowledge capture [240] and push through monitoring of engineering design tasks and resulting in profiles that can be used in ways to improve CAD support, give advice for a more efficient design and allow for the automation of design rationale and decision making. [78, 237, 240]. Game GUIs with their contextual menus and interfaces might be something to explore to help enhance CAD; for example 3DMax [241] has been using a contextual GUI for a few years (modelling, animating, rigging and rendering/production), Blender [188] which also enables solid modelling designing, with fully customisable interface and non-overlapping and non-blocking UI. Why not use any of those GUI features in the design environment of CAD?

Finally game engines and particularly their physics engines for interactive real-time physics simulation have a high degree of potential not just only for the computer games but also for production industries as an aid for better understanding of physically complex systems. Game engines can be viewed as tools which help engineers understand physical systems and enable them to explore the complexities of such systems. However, there is a discussion whether game engines and specifically the component of the physics engine can deal accurately with the number of complexity of geometric features present in a CAD model in a physics-based simulation [242]. Indeed the performance evaluation of the physics engines in engineering design has yet to be researched. However physics engines have been compared for their performance criterion and accuracy.

Seugling and Rölin [243] compared three physics engines; Newton; ODE and PhysX SDK. Their comparison criteria were: friction on a sliding plane, gyroscopic forces, restitution, stability of constraints, accuracy against real, scalability of constraints (multiple joints), scalability of contacts (pile of boxes), stability of piling (max number of stacked boxes), complex contact primitive-mesh, convex-mesh and mesh-mesh. Their results shown that PhysX, was the best evaluated simulation engine except in the stability of piling test and the mesh-mesh collision detection. Boeing and Bräunl [244] in their investigation compared PhysX, Bullet, JigLib, Newton, ODE, Tokamak and True Axis using Physics Abstraction Layer (PAL). The engines were compared against the integrator performance, material properties, friction, constraint stability, collision system and the stacking test. They concluded that PhysX had the best integrator method whereas Bullet provided the most robust collision system. Finally Coumans and Victor [255] compared the following physics engines: PhysX, Havok, ODE and Bullet. Their comparison criteria included collision detection and rigid body features. The authors suggested that PhysX was the most complete engine.

Game engines and their advanced “gaming physics” are capable of delivering physics capability for simulations other than in the entertainment area. Future CAD will reflect not only the current multi-functional engineering environment but also physics mathematics simulations based on the Newtonians game engines such as CryEngine [109] (Fig. 15).

Fig. 15 Future CAD and the “gaming physics” simulations

5 Conclusions

As has been shown in this review, the extensive use of game technologies and game elements in a wide range of domains indicates that there is considerable potential to embed these as useful components within future CAD systems. Table 8, in particular, provides a comparison which highlights some opportunities for research in this area. Future CAD could use 3D visualisation in a wide variety of domains, such as VR and mobile tablets, sensors for real time tracking designer behaviour and analytical tools. It may also provide the capability to integrate real time knowledge capture and knowledge push as the engineer is monitored and their activities analysed as they carry out engineering tasks [224-225]. However, in addition to this type of functionality, game GUIs with contextual menus and interfaces will also provide new, enjoyable and more intuitive experiences through which engineers can generate concepts and detailed designs within CAD.

This review does not claim that all game elements and UX theories are relevant to CAD engineering design but, as has been highlighted, a significant number may be relevant. However, further research is required to deepen the understanding of game-related elements and the enhancement of the user experience in engineering design.

Design is both associated with the generation of virtual objects as well as being the precursor to the manufacture of physical objects. There is need for design innovations and inventions. Games with their associated stimulating environments provide a rich opportunity to engage people in carrying out tasks; therefore, why not engineers in their product development activities? It has been shown that games are inherently cross-disciplinary and can be applied to many disciplines; engineering can be one of them.

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Vitae

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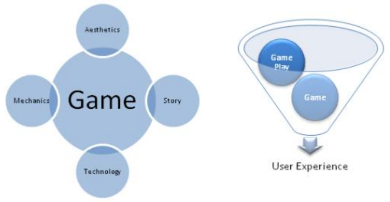

Fig.1 Game elements and the user experience (UX)

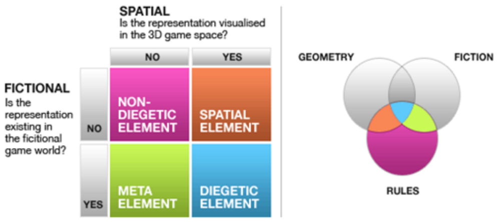

Fig. 2 Game UI elements [96]

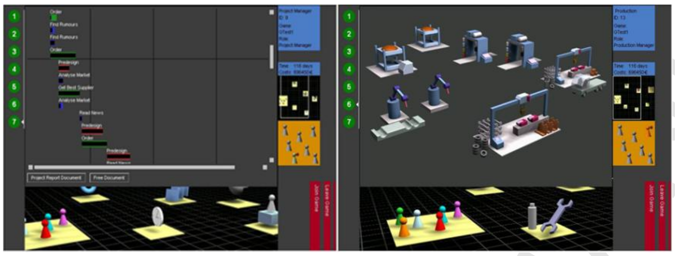

Fig. 3 COSIGA: Product design and project management for scenario truck [140]

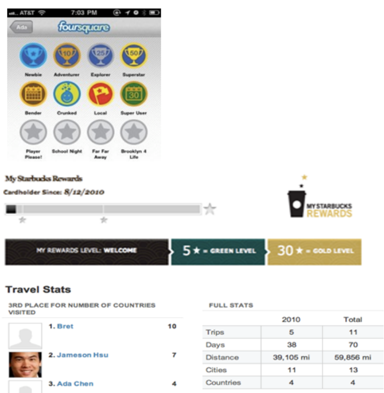

Fig. 4 Game mechanics applications in marketing brands [161]

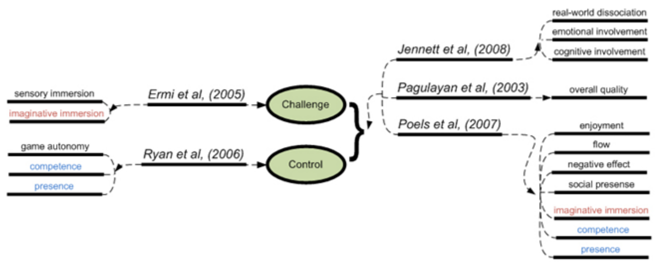

Fig. 5 Diagram summarizing the game-relevant issues and models

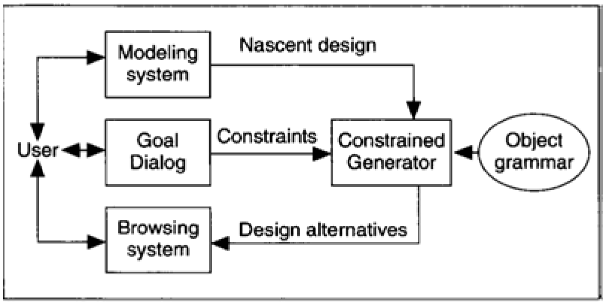

Fig. 6 CCAD system architecture [224]

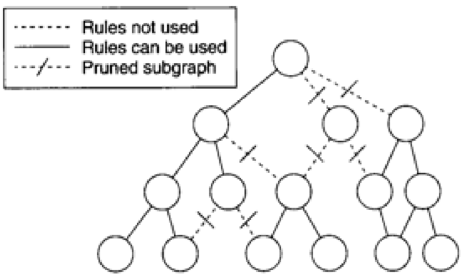

Fig. 7 Selecting specific rules for research alternative ideas [224]

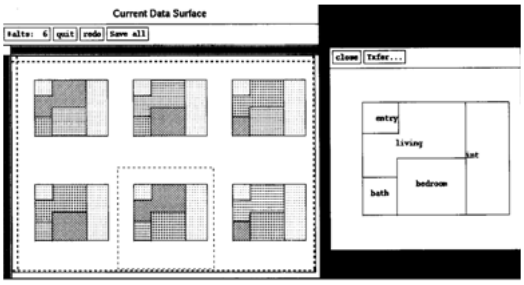

Fig. 8 Rules for subdividing the house into night and day areas [224]

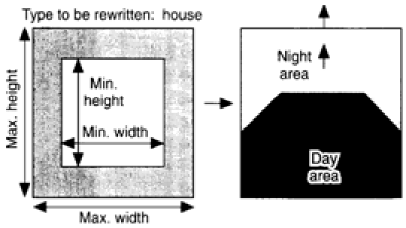

Fig. 9 The interface of browsing through alternative designs [224]

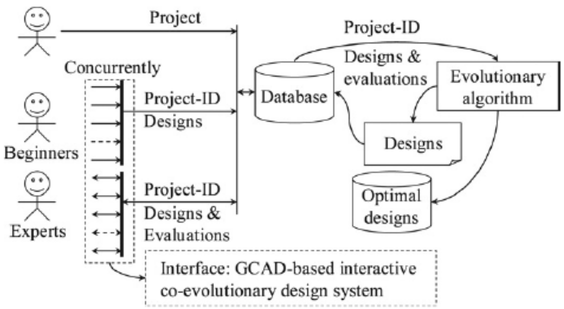

Fig. 10 Data flow in the interactive co-evolutionary GCAD system [225]

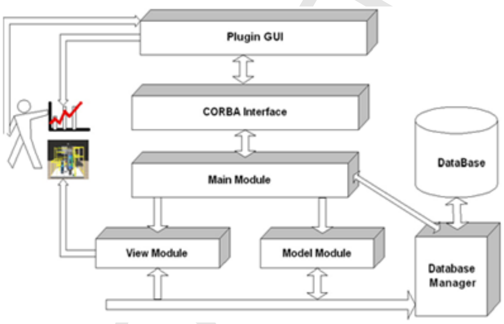

Fig. 11 Diagram of the System Architecture [226]

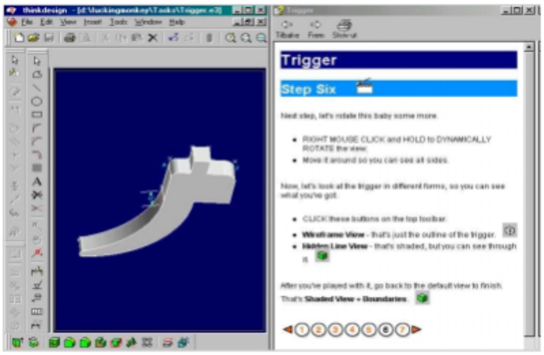

Fig.12 The Monkey Wrench Conspiracy CAD-game interface [230]

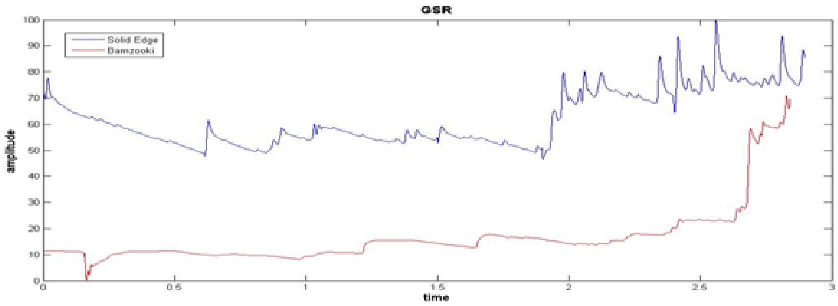

Fig. 13 Participant's GSRs while designed in both interfaces. The top line is the GSR in Solid Edge and the bottom in BAMZOOKi [231]

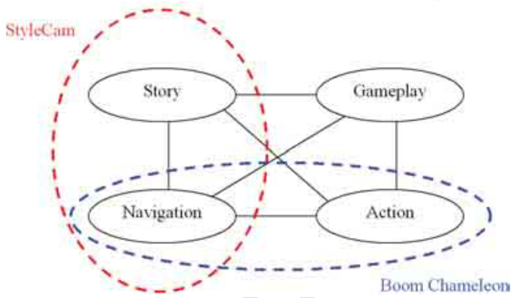

Fig. 14 Experimental components of games [236]

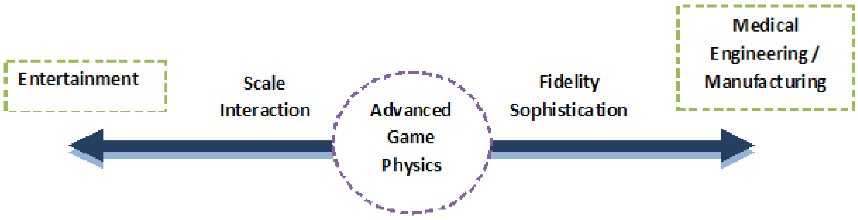

Fig. 15 Future CAD and the “gaming physics” simulations

Tables

Table 1 CAD Categories

■ Knowledge based [36-38], Feature-based [56], Case-based [57], Biologically-inspired [58], Parametric [39-40]
■ CAD Modeling - Surface (NURBS) [41-42], Solids [59], Constructive Solid Geometry [60], Primitive [61], Physics-based [43-44]
■ Domain - MCAD (mechanical) [48-50], ECAD (Electrical) [62], Medical CAD [48-50]
■ Platform - Desktop, VR [51-53], Haptic [54-55]

Table 2 Current modelling CAD features

Main features:	• **Keeps track of design dependencies** • **Design figures and curves in 2-D** • **Design surfaces, curves and solids in 3-D** • **View of design from any angle - Rotate** • **Zoom options for close up or long distance views** • **Simulation**	• **3D geometry input** • **Assembly Modelling** • **Digital Prototyping** • **Electronic Database** • **Easy Reproduction** • **Savings in Cost** • **Access Control - Secure file handling** • **Parametric Drawing**
Additional features based in a variety of software: Autodesk Inventor 2011, SolidWorks 2010, Creo Elements /Pro 2010, Punch, TurboCAD 16, ZWCAD, Alibre Design Expert 2011, IronCAD Inovate 2011, Solid Edge ST3, Siemens NX 7	• Annotation| Scaling | Rendering | Measuring • Sheet Set Manager(organize your drawings and link sheet set information) | Data logging | Report generation | Data Extraction (output object's property data) | document management | Data translation • Customized user interface | Programming Interfaces • Surfacing tools | Sheet metal design | Plastic parts design | Tube and Pipe design | Cable and Harness design | • Analysis design; structural, vibration, durability, heat and motion performance analysis | Interface Detection Errors | Help assistance | Tracking tools for geometric information against specification | Intelligent design analysis (run possible scenarios)	• Automation features; Highlighting and tagging of dimensions, Rapid dimensions, Feature recognition | Assembly memory management | Manufacturing patterns recognition | Automatic tool path generation | • Dynamic Assembly Motion | Physical Simulation | Simulation of nonlinear large deformation, hyper-elasticity, assembly connectivity, friction-added surfaces, temperature, vibration, dust, humidity | pre-defined animation paths • Print 3D models |Knowledge capture / process database | Conceptual design tools | Reverse engineering | Part libraries | Design communication – collaboration capabilities | Synchronous technology | CAM • Welding Application | Mold /Casting Application

Table 3 Summary of studies in CAD usage

Research area	**Authors**
Efficiency limits in CAD	Waern [68-69], Luczak et al [72], Muller [73], Ghang Lee et al [79]
Limited creativity in CAD	Waern [68-69], Cooley (cited by Parletun et al [70]), Black [71], Dickinson et al [76], Petre [77], Robertson [81-82], Charlesworth [73]
Lack of user's motivation in CAD (suboptimal use)	Bhavnani et al [74] Charlesworth [80]
Limited interaction	Stacey et al [75]

Table 4 Game Mechanics definitions based on the paper of Sicart [92]

Authors	**Game Mechanics Definitions**
Avedon (1971)	A formal structure of games in which there are specific operations requires courses of action, method of play - the procedure for action which is fixed principles that determine conduct and standard behaviour.
Lungren Bjork (2003)	Any part of the rule system of a game that cover one, and only one, possible kind of interaction that takes place during the game, be it general or specific. Mechanics are regarded as a way to summarize the rules.
Richard Rouse (2005)	The guts of a design document, as they describe what the players are able to do in the game world, how they do it, and how that leads to a compelling game experience.
Fullerton, Hoffman and Swain (2004)	The actions or methods of play allowed by the rules (..) they guide player behaviour, creating interactions
Cook (2005)	Game mechanics are rule based system / simulations that facilitate and encourage a user to explore and learn the properties of their possibility space through the use of feedback mechanisms.
MDA framework - Hunicke, Zubek, Leblanc (2004)	Mechanics describes the particular components of the game, at the level of data representation and algorithms (...) mechanics are the various actions, behaviours and control mechanisms afforded to the player within a game context.
Jarvinen (2008)	Means to guide the player into particular behaviour by constraining the space of possible plans to attain goals. Game mechanics are described with verbs and therefore, “take cover” would be a core mechanic for a game like Gears of war (Microsoft game, 2007). Rules are a particular set of rules available to the player in the form of prescribed causal relations between game elements and their consequence to particular game states.
Sicart (2008)	*"...Game mechanics are methods invoked by agents, designed for interaction with the game state".* Where methods are behaviours, actions and functions available to the agent (player, or AI of system) within the constraints of a game environment.

Table 5 Game mechanics elements (Resource: SCVNGR's Secret Game Mechanics Playdeck [93])

1. Achievement	2. Appointment Dynamic	3. Avoidance
4. Behavioural Contrast	5. Behavioural Momentum	6. Blissful Productivity
7. Cascading Information Theory	9. Communal Discovery	10. Companion Gaming
11. Contingency	12. Countdown	13. Cross Situational Leader-boards
14. Disincentives	15. Endless Games	16. Envy
17. Epic Meaning	18. Extinction	19. Fixed Interval Reward Schedules
20. Fixed Ratio Reward Schedule	21. Free Lunch	22. Fun Once, Fun Always
23. Interval Reward Schedules	24. Lottery	25. Loyalty
26. Meta Game	27. Micro Leader-boards	28. Modifiers
29. Moral Hazard of Game Play	30. Ownership	31. Pride
32. Privacy	33. Progression Dynamic	34. Ratio Reward Schedules
35. Real-time v. Delayed Mechanics	36. Reinforcer	37. Response
38. Reward Schedules	39. Rolling Physical Goods	40. Shell Game
41. Social Fabric of Games	42. Status	43. Urgent Optimism
44. Variable Interval Reward Schedules	45. Variable Ratio Reward Schedule	46. Viral Game Mechanics
47. Virtual Items		

Table 6 Physics engines' destruction methods based on [123]

Physics engines: Destruction methods		Game/Application
Real-time Boolean	Subtraction and addition of solid objects in real time.	Red Faction games [124]
Particle	Connection of neighbouring particles by links to form one 1D rope (2 particles) or 2D triangle (3 particles), or tetrahedron (4 particles). Additional links between particles can simulate bending constraints and shearing constraints. The way to simulate motion can be achieved through forces and accelerations formulations or position formulations.	Gerbil Physics game [125]
Finite Element	Simulating deformation and fracture based on continuum mechanics. A 3D mesh is approximated using a collection of elements, usually tetrahedra. The strains, stress and stiffness matrix is used to compute the effect of forces and deformations.	Real-time simulations for material effects [126]
Rigid body & Hybrid	Composed by single rigid body of fractured pieces "glued" together with assigned connections between each piece or based on collision detection computations. Another way to control the fractures is through the hybrid method and finite element method to compute the strain and stress. If the FEM analysis determines that the object should break, the object breaks its rigid bodies into multiple pieces.	Angry Bird game [127]

Table 7 Game Mechanics and their effects in the specified domains

Domain	Games	Game mechanic	Effect
Education			
Physics	Fluidity, Bridge Builder	Achievement, Rewards Schedules, Virtual Items, Micro-Leaderboards (Competition)	Problem-Solving skills, Creativity, Logical skills
Concurrent Engineering	COSIGA	Disincentives, Micro-Leaderboards (Competitio)	Training, Management
Business Management	Based on game The Sims; AirwaySim, Business Tycoon, Capitalism, Hollywood Mogul, Virtonomics, Industry Player	Blissful productivity (performing a useful and rewarding work), Disincentives, Endless Games, Micro-Leaderboards (Competition)	Problem-Solving skills, Creativity, Management, Marketing, HR Trading , Logistics and Finance skills
Social	Food Force, Re-Mission, Darfur is Dying, Reach out Central	Behavioural contrast, Disincentives, Cascading Information Theory	Involvement, Society-World Politics, Awareness, Behaviour Change
Medicine	Triage Trainer, Pulse, Dental Implant Training Simulation	Disincentives, Cascading Information Theory	Training, Problem-Solving & Decision-making skills, Prioritising
Military	McCurdy's Armor , Virtual Battlespace 1& 2, Virtual Combat Convoy Trainer, American Army, Secure the Deck	Behavioural contrast, Disincentives, Cascading Information Theory	Training, Problem-Solving & Decision-making skills, Assessment Risks, Information Sharing
Marketing	Foursquare, My Starbucks Rewards, Tripit	Status, Achievements, Rewards Schedules, Virtual Items, Micro-Leaderboards (Competition), Free Lunch	Brand awareness, Build loyalty

	Configurators	Fun once-Fun always	Brand awareness, Build loyalty
Software Engineering	Visual Studio Game add-on	Status, Achievements, Rewards Schedules, Virtual Items, Micro-Leaderboards (Competition)	Knowledge gathering (explore unknown features) Contribution & Recognition, Commitment

Table 8 Game characteristics, CAD and Effect

Games Elements and Characteristics		**Limited CAD Aspects**
Game Mechanics	Process of use; gameplay	Results of the processes
	Goals defined by game world & System's performance feedback	Goals defined by task requirements & Manager's performance reports
	Variable Difficulty Level (e.g. for score keeping); GUI has successive layers of complexity	No Difficulty Levels; GUI organised on design tasks
Aesthetics and the Graphical User Interface (GUI)	Different representation tools and customise UI elements Graphical Richness	Limited customizability (if available) & no multiple integrated representations
	Randomness & Humour	--
	Use of communications strategies: Introduce new information when knowledge is incomplete and inconsistent	Limited Assistance and constructive Feedback
	Metaphors	--
	Variety of interactive devices	Force Feedback devices
Games Technology	Continuous innovation in content and control; game engines	Development in designing product visualisation (e.g. VR)
User Experience	Variety of experiences Emotionally Appealing Cognitive Models; Metaphors	Experiences not consistent
	Mood & Motivation	Functionality but not usability